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Resonance Control System for PIP-II 650 MHz STC at Fermilab

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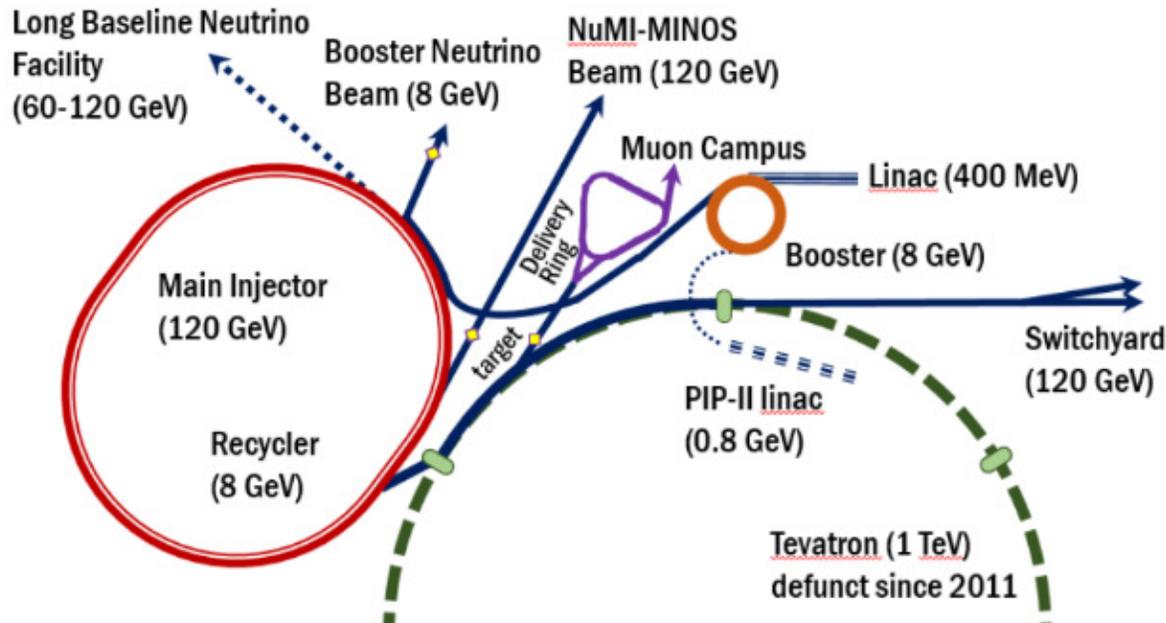
L. Doolittle, C. Serrano, S. Paiagua, LBNL

Resonance Control for 650 MHz STC

2 October 2019



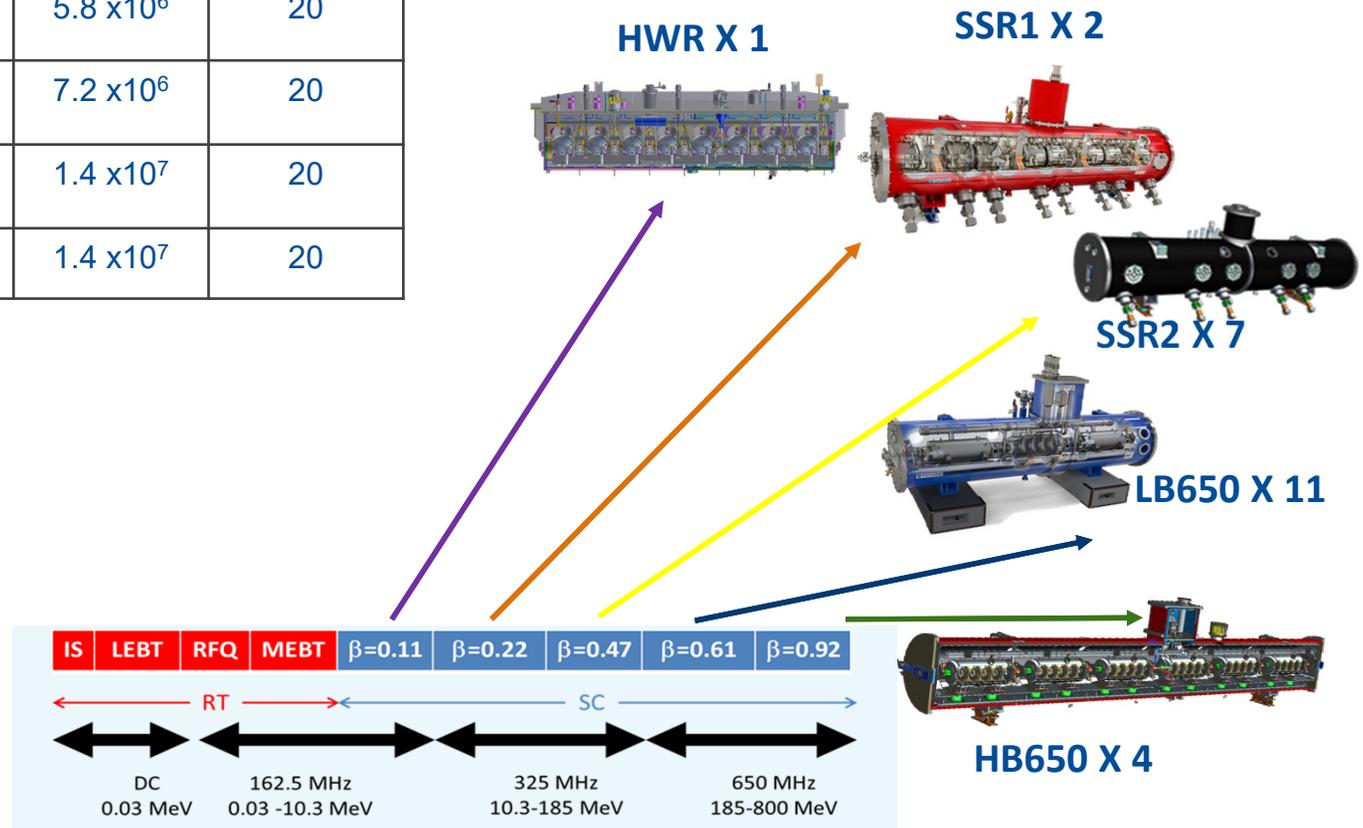
PIP-II Project



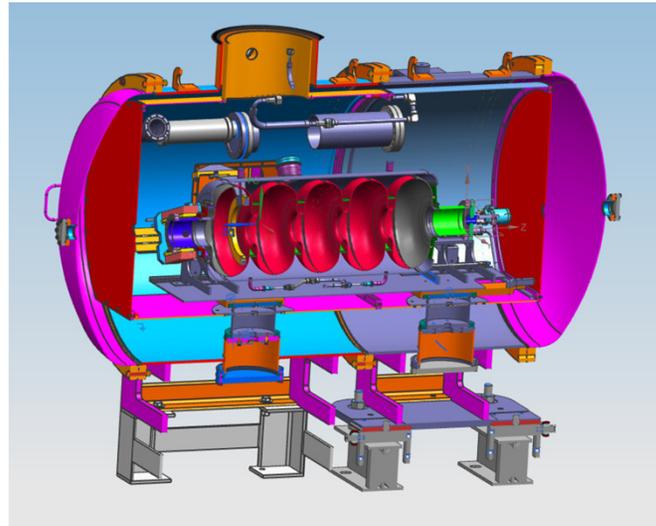
PIP-II is a 800 MeV SRF Linac to replace the current 400 MeV Linac

PIP-II Cryomodules

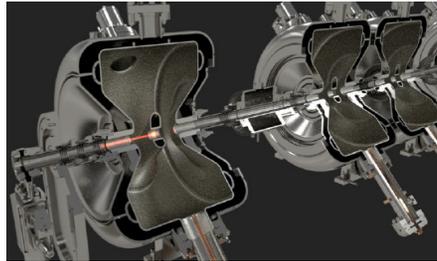
Cavity	f_0 (MHz)	$f_{1/2}$ (Hz)	Q_L	Δf_{peak} (Hz)
HWR	162.5	24.6	3.3×10^6	20
SSR1	325	28	5.8×10^6	20
SSR2	325	22.6	7.2×10^6	20
LB650	650	23.2	1.4×10^7	20
HB650	650	23.2	1.4×10^7	20



STC 650 Test Stand



HWR



SSR1

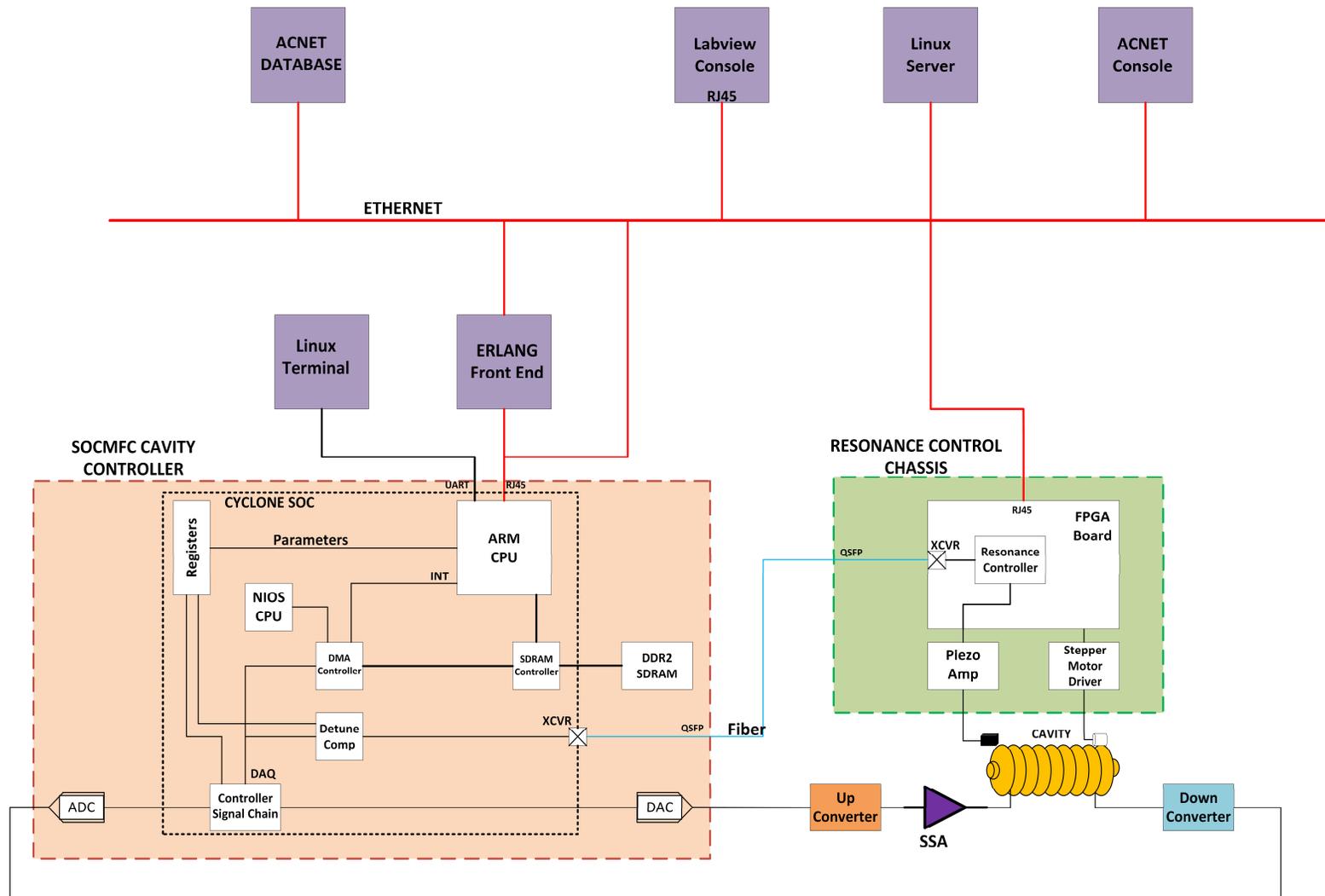


LB650

Test Stand Requirements

- Qualify 650 MHz elliptical cavities(HB and LB) during horizontal test (with coupler, tuner, He vessel, magnetic shield) before cryomodule fabrication.
- Capability to support testing of 325 MHz $\beta=0.22$, SSR1 and $\beta=0.47$ SSR2 cavities.
- LLRF system with RF Field control, Cavity Resonance Control , Data Acquisition system and capability to measure cavity parameters.

Test Stand LLRF System



Resonance Control

- Cavity detuning computation
- Piezo control to cavity detuning modeling – Transfer Function measurement/estimation
- Microphonics measurement
- Controller simulation and design
- Resonance control testing and validation

Detuning Computation

Cavity Envelop Equation

$$\frac{d\vec{V}}{dt} = a\vec{V} + b\vec{K}_1$$

$$a = j\omega_d - \frac{1}{2}\omega_0 \left(\frac{1}{Q_0} + \frac{1}{Q_1} \right)$$

$$b = \omega_0 \sqrt{\frac{(R/Q)}{Q_1}}$$

$$\Re(a) = -|b|^2 \cdot \frac{1}{2\omega_0(R/Q)}$$

$$\vec{V} = c_V \cdot \vec{M}_V \quad \text{Cavity Probe}$$

$$\vec{K}_1 = c_K \cdot \vec{M}_K \quad \text{Forward Power}$$

$$\frac{d\vec{M}_V}{dt} = a\vec{M}_V + \left(b \frac{c_K}{c_V} \right) \vec{M}_K$$

$$\beta \equiv b(c_K/c_V)$$

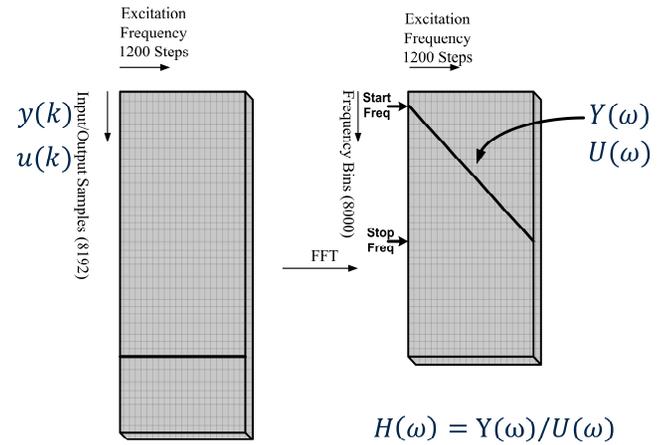
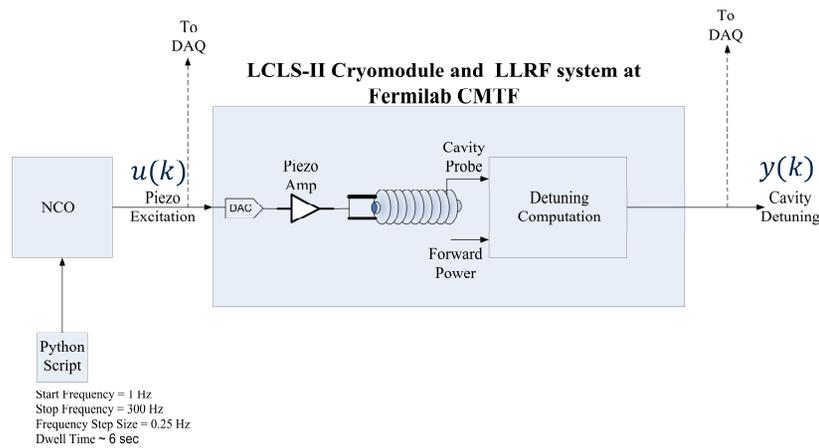
$$\frac{c_K}{c_V} = \frac{\sqrt{-2\omega_0(R/Q)\Re(a)}}{|\beta|}$$

$$a = \frac{1}{\vec{M}_V} \cdot \left[\frac{d\vec{M}_V}{dt} - \beta \vec{M}_K \right]$$

Detuning Calibration

- Apply short RF pulses followed by passive decay
- Record Probe and Forward power waveforms M_V, M_K
- Store calibration constants c_M, c_K and β
- Compute the derivative $\frac{dM_V}{dt}$
- Solve for a (complex) and b(real)
- Computation block can pipeline the math efficiently and provide ~6kHz rate using minimal FPGA resources

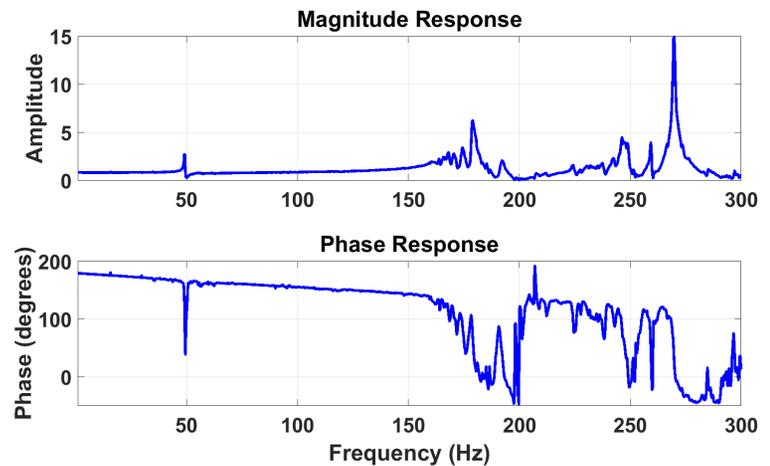
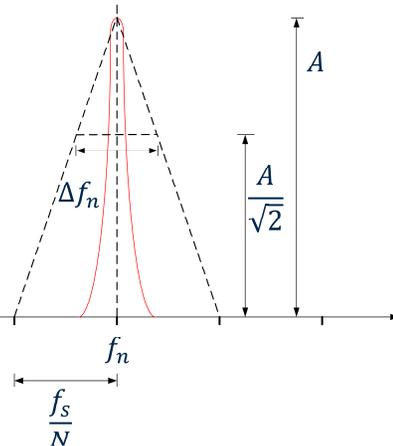
Transfer Function Measurement



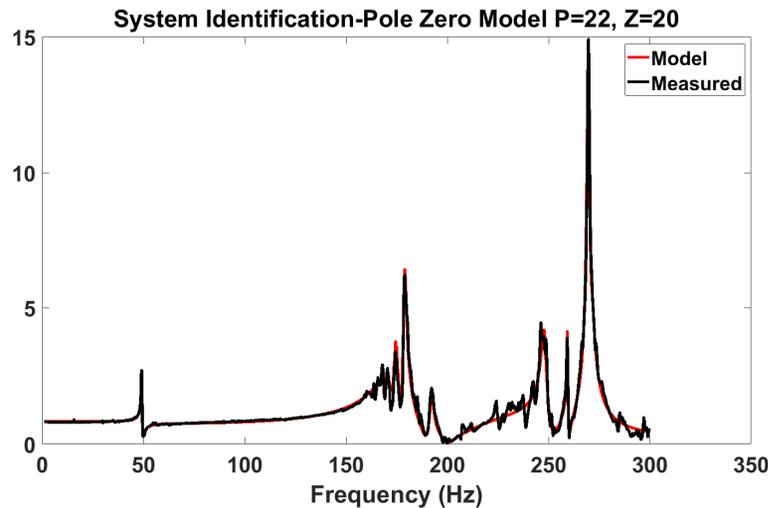
$$Q_{max} = \frac{f_n}{\Delta f_n} = \frac{N f_n}{2 f_s (1 - 1/\sqrt{2})}$$

f_n	Q_{max}
5	34
10	68
50	340
100	683
150	1024
200	1366
300	2049

$f_s = 2$ kHz
 $N = 8000$
 Freq Step = 0.25 Hz



Model Fit using System Identification



$$x(k+1) = Ax(k) + Bu(k), \quad A \rightarrow n \times n, B \rightarrow n \times r$$

$$y(k) = Cx(k) + Du(k), \quad C \rightarrow m \times n, D \rightarrow m \times r$$

- A SISO system has $r, m = 1$
- Eigen values of A represent the poles of the system
- The imaginary part represents resonant frequencies f_n

$$P = [B \ : \ AB \ : \ A^2B \ : \ \dots \ : \ A^{21}B] , \quad P \rightarrow 22 \times 22$$

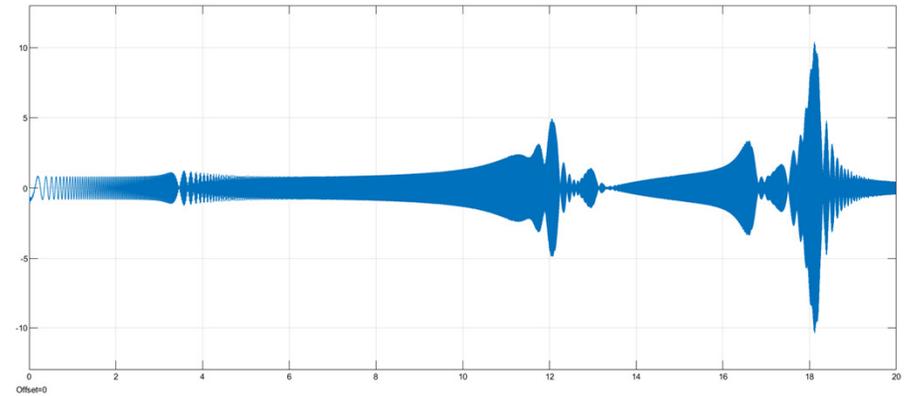
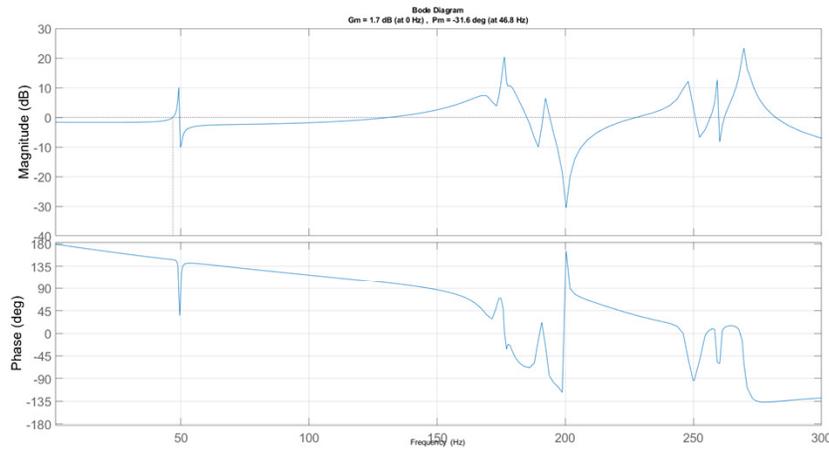
$$Q = [C^T \ : \ A^T C^T \ : \ (A^T)^2 C^T \ : \ \dots \ : \ (A^T)^{21} C^T] , \quad Q \rightarrow 22 \times 22$$

$$\text{Rank}(P) = 22, \quad \text{System Controllable (Stabilizable)}$$

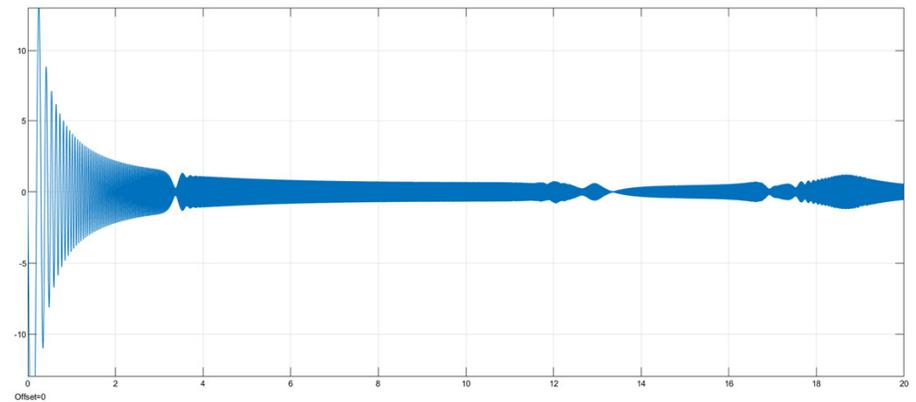
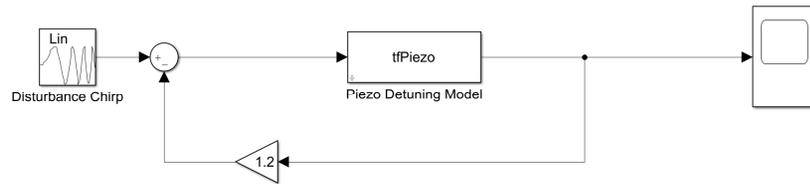
$$\text{Rank}(Q) = 14, \quad \text{System not Observable (Detectable)}$$

0	49	172	174	180	192	223	248	259	270	271
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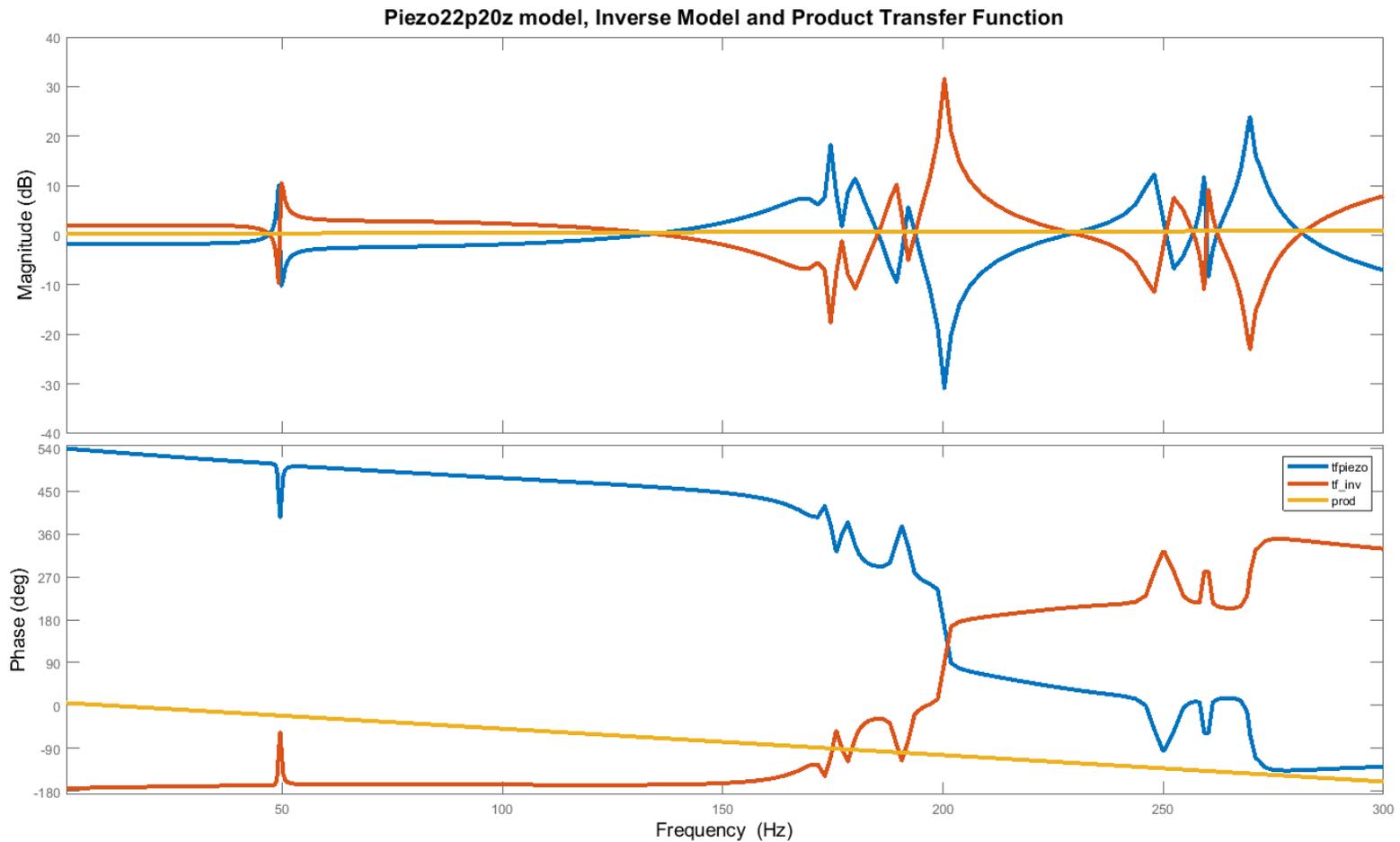
Controller Design and Simulation



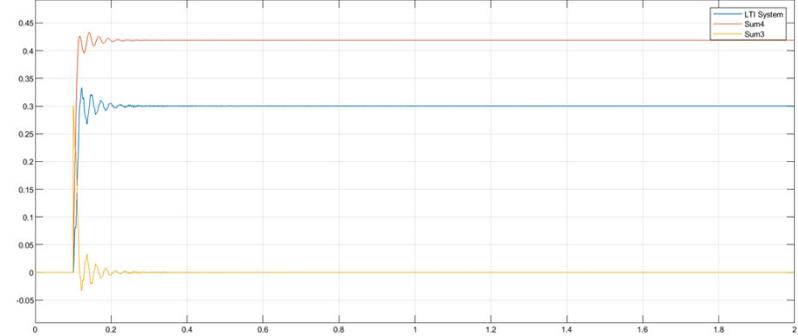
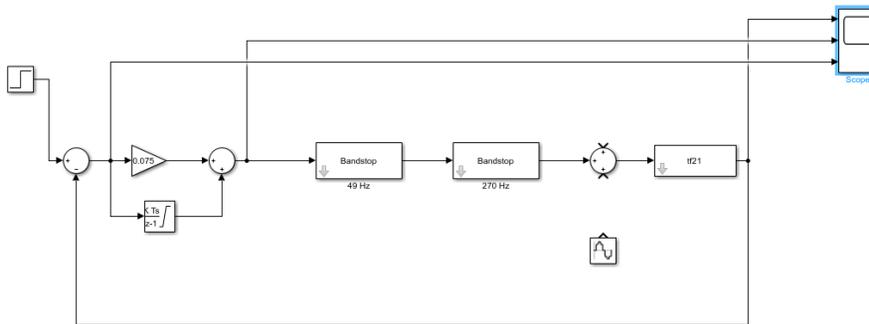
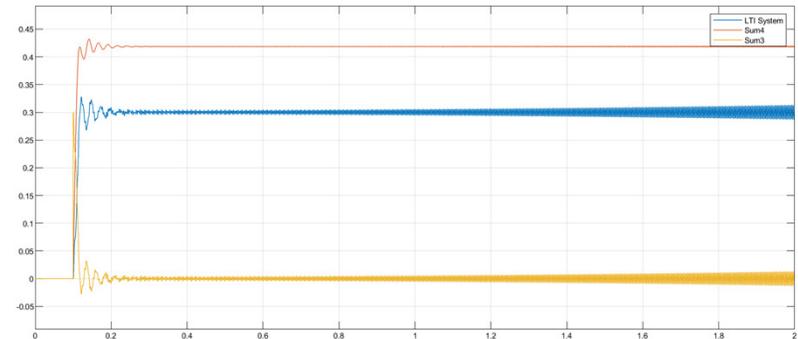
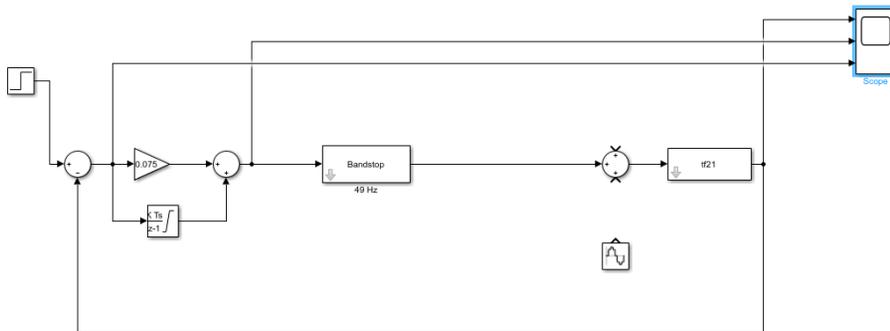
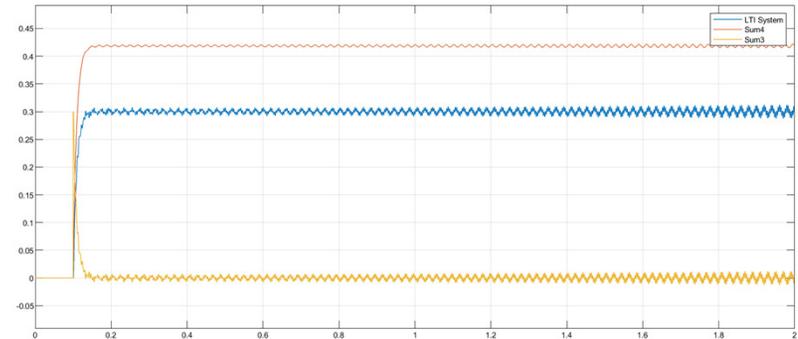
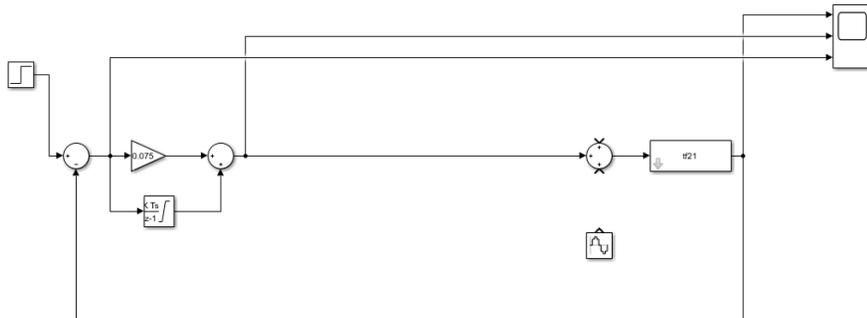
Direct Feedback with proportional gain only



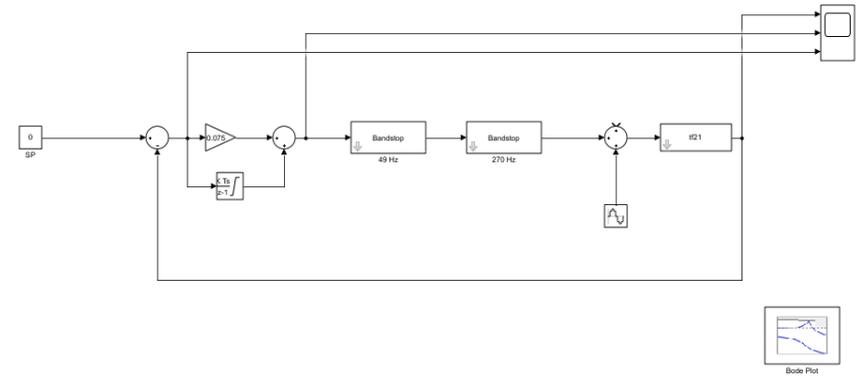
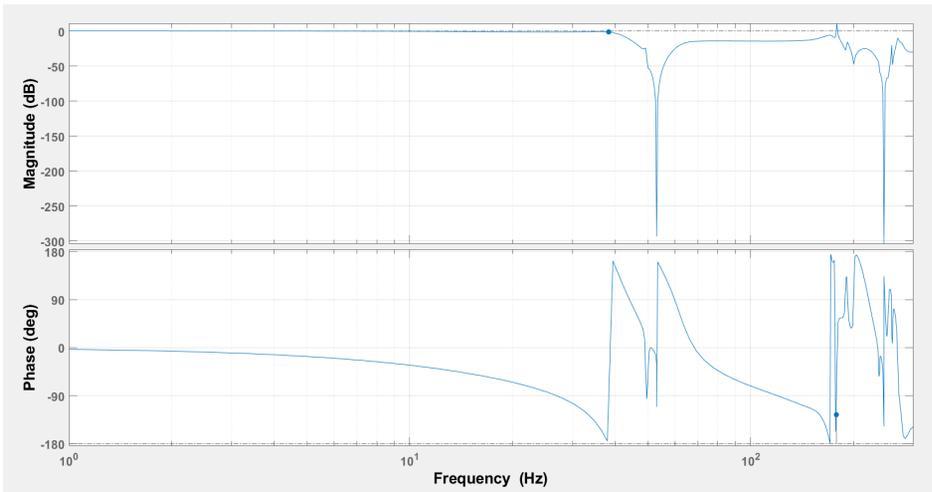
Controller as Inverse of Model



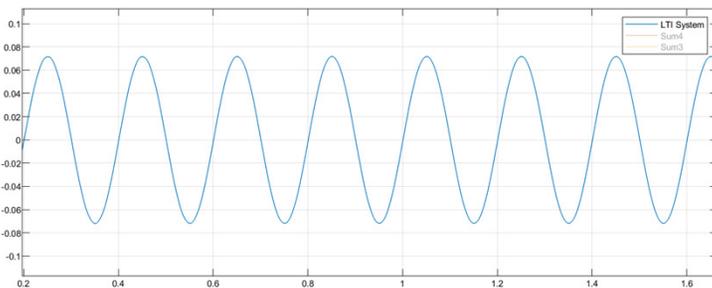
DC Stability with Integral Control



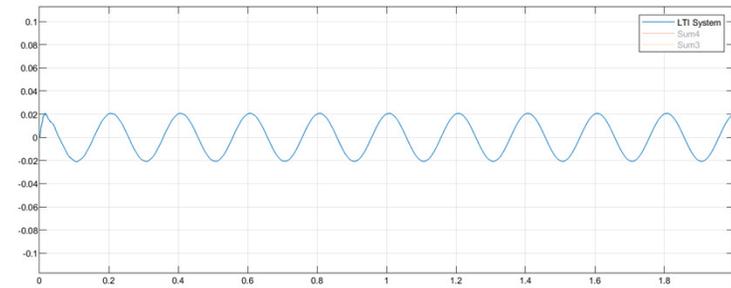
Closed Loop Frequency Response



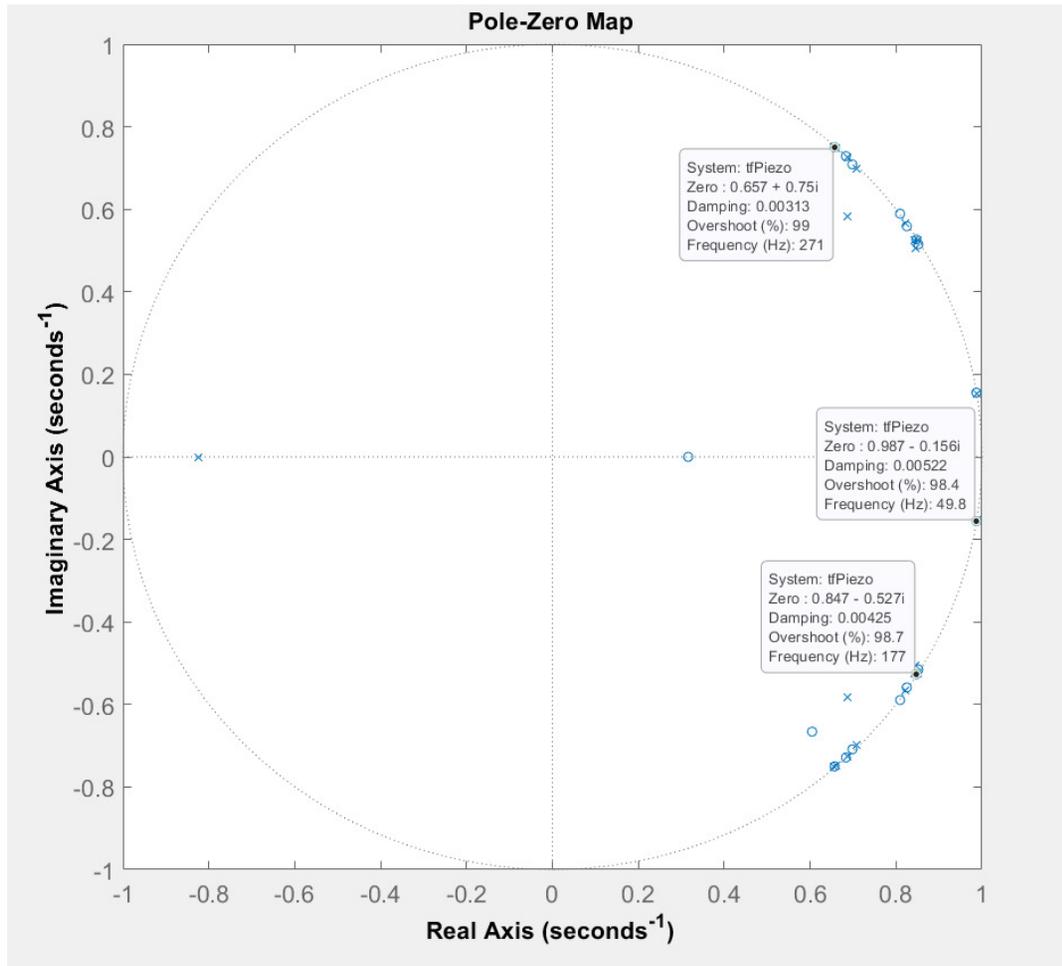
5 Hz Disturbance



~11dB



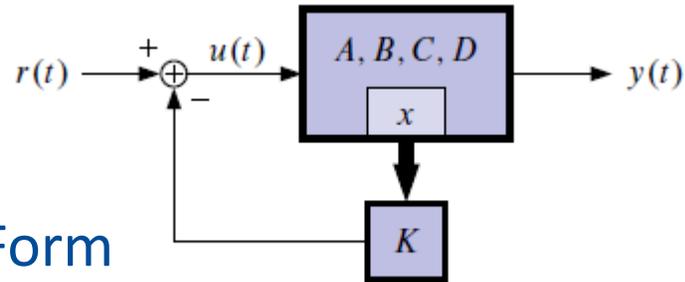
Pole Zero Locations at Resonance Frequencies



0.986971365339206 +	-0.825351180697489 +
0.155742284022236i	0.00000000000000i
0.986971365339206 -	0.987563141804534 +
0.155742284022236i	0.153817010278278i
0.657234402718026 +	0.987563141804534 -
0.750155251845808i	0.153817010278278i
0.657234402718026 -	0.656342634352271 +
0.750155251845808i	0.750230330245834i
0.604631337432134 +	0.656342634352271 -
0.665979757660314i	0.750230330245834i
0.604631337432134 -	0.660651346930355 +
0.665979757660314i	0.747984635542678i
0.683324441848158 +	0.660651346930355 -
0.728741763313030i	0.747984635542678i
0.683324441848158 -	0.685658246290726 +
0.728741763313030i	0.726858814251725i
0.698372477326451 +	0.685658246290726 -
0.708891173607357i	0.726858814251725i
0.698372477326451 -	0.708678215678216 +
0.708891173607357i	0.699639432251094i
0.809541682374210 +	0.708678215678216 -
0.589383966245636i	0.699639432251094i
0.809541682374210 -	0.687957528668362 +
0.589383966245636i	0.582772802721014i
0.851990291401923 +	0.687957528668362 -
0.515145683607570i	0.582772802721014i
0.851990291401923 -	0.821089913582197 +
0.515145683607570i	0.566590869301807i
0.847219679912761 +	0.821089913582197 -
0.526789324848282i	0.566590869301807i
0.847219679912761 -	0.844738881940333 +
0.526789324848282i	0.506879984738050i
0.825135646189367 +	0.844738881940333 -
0.558765174615488i	0.506879984738050i
0.825135646189367 -	0.849450338479423 +
0.558765174615488i	0.525108024290633i
0.316166689887343 +	0.849450338479423 -
0.00000000000000i	0.525108024290633i
	0.842811256380781 +
	0.525612220606421i
	0.842811256380781 -
	0.525612220606421i

Pole Placement by State Feedback

Controller Canonical Form



$$T^{-1}AT = A_c = \begin{bmatrix} -a_1 & -a_2 & \cdots & -a_n \\ 1 & & & 0 \\ & \ddots & & \vdots \\ 0 & \cdots & 1 & 0 \end{bmatrix} \quad \text{and} \quad T^{-1}B = B_c = \begin{bmatrix} 1 \\ 0 \\ \vdots \\ 0 \end{bmatrix}$$

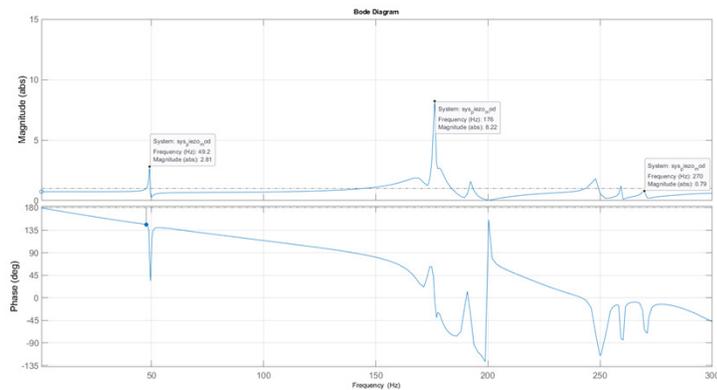
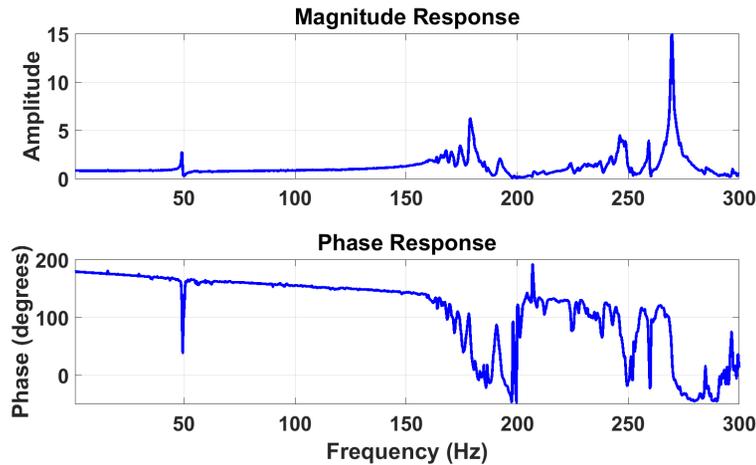
where $\det(sI - A) = s^n + a_1s^{n-1} + \cdots + a_n$.

$$K = \left[(\alpha_1 - a_1) \quad \cdots \quad (\alpha_n - a_n) \right] \begin{bmatrix} 1 & a_1 & \cdots & a_{n-1} \\ 0 & 1 & & a_{n-2} \\ \vdots & & \ddots & \vdots \\ 0 & & & 1 \end{bmatrix}^{-1} C^{-1}.$$

$K = \text{place}(A, B, \text{poles});$

Bass – Gura Formula

Pole placement to Reduce Resonance Peaks



0.986971365339206 + 0.155742284022236i	-0.825351180697489 + 0.00000000000000i
0.986971365339206 - 0.155742284022236i	0.987563141804534 + 0.153817010278278i
0.657234402718026 + 0.750155251845808i	0.987563141804534 - 0.153817010278278i
0.657234402718026 - 0.750155251845808i	0.556342634352271 + 0.750230330245834i
0.604631337432134 + 0.665979757660314i	0.556342634352271 - 0.750230330245834i
0.604631337432134 - 0.665979757660314i	0.660651346930355 + 0.747984635542678i
0.683324441848158 + 0.728741763313030i	0.660651346930355 - 0.747984635542678i
0.683324441848158 - 0.728741763313030i	0.685658246290726 + 0.726858814251725i
0.698372477326451 + 0.708891173607357i	0.685658246290726 - 0.726858814251725i
0.698372477326451 - 0.708891173607357i	0.708678215678216 + 0.699639432251094i
0.809541682374210 + 0.589383966245636i	0.708678215678216 - 0.699639432251094i
0.809541682374210 - 0.589383966245636i	0.687957528668362 + 0.582772802721014i
0.851990291401923 + 0.515145683607570i	0.687957528668362 - 0.582772802721014i
0.851990291401923 - 0.515145683607570i	0.821089913582197 + 0.566590869301807i
0.847219679912761 + 0.526789324848282i	0.821089913582197 - 0.566590869301807i
0.847219679912761 - 0.526789324848282i	0.844738881940333 + 0.506879984738050i
0.825135646189367 + 0.558765174615488i	0.844738881940333 - 0.506879984738050i
0.825135646189367 - 0.558765174615488i	0.849450338479423 + 0.525108024290633i
0.316166689887343 + 0.00000000000000i	0.849450338479423 - 0.525108024290633i
	0.842811256380781 + 0.525612220606421i
	0.842811256380781 - 0.525612220606421i

Conclusions

- A LLRF system for the 650 MHz Test Stand has been developed
- Resonance Control for multiple cavity types will be needed for the PIP-II project
- The test stand and other PIP-II near term projects are a collaboration between Fermilab and LBNL LLRF teams
- A few control design approaches have been explored
- PIP II offers many challenges to create Resonance Control solutions for a variety of cavity types.
- Modeling the piezo to cavity detuning dynamics is a key to developing effective control algorithms.